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Observation of strongly deformed shapes in $^{154-152}$Dy nuclei at medium temperatures

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The γ-decay of the giant dipole resonance (GDR) built on excited states of $^{154-152}$Dy nuclei is studied. The selection of GDR decay from high spin states leading to specific exit channels was made possible by triggering on high spin isomers. The deduced energy splitting of the GDR implies large deformations ($|\beta| \simeq 0.4$–0.5). The resonance widths of the components are comparable to those of the GDR built on the ground state indicating small shape fluctuations.

In recent years, the study of the statistical γ-decay of the giant dipole resonance (GDR) in hot nuclei has been widely used as a tool to investigate the evolution of nuclear structure as a function of temperature (excitation energy) and angular momentum [1–5]. The γ-rays, which de-excite the GDR, are emitted in direct competition with particle decay in the first steps of the decay of compound nuclei produced in heavy ion fusion reactions. In analogy with the GDR built on the ground state [6], the shape of the GDR strength distribution observed in the γ-decay of hot compound nuclei is expected to reflect the properties of the ensemble of excited nuclear states populated. The first signs of nuclear deformation effects on the γ-spectra from the decay of compound nuclei were observed by Gaardhøje et al. [7] and Gossett et al. [8]. Although these first results looked promising, it appears to be very difficult to extract unambiguously the prolate or oblate character of the nuclear shape from the high energy γ-spectra alone [2,9,10].

The experimental accuracy is not the only factor which limits the amount of information which can be extracted from the analysis of the high energy γ-spectra. Other limiting factors are: (a) the γ-spectra are composed of contributions from several nuclei, with a wide range of excitation energy and angular momentum; (b) different nuclear shapes coexist in one nucleus, and at higher temperatures thermal fluctuations of the shape and orientation of the nucleus can become large. These fluctuations tend to increase the GDR width with increasing thermal excitation energy [11–13]. Moreover, the γ-rays originating from the GDR decay are superimposed on an exponentially decreasing continuum of statistical γ-rays which seriously diminishes the sensitivity to GDR-associated γ-rays below 10 MeV. This sensitivity can be improved by selecting events in which fewer neutrons (i.e. one neutron less) are emitted than expected from the available excitation energy. Only a few experiments, in which the GDR γ-rays are enhanced by measuring in coincidence with a particular decay channel, have been performed [14–16].

In the present work the identification of specific reaction channels from the depopulation of excited states in ^{154}Dy* was accomplished by triggering on the decay of known high spin isomeric states: ^{152}Dy ($J^\pi = 17^+$, $\tau = 60$ ns, 2n), ^{151}Dy ($J^\pi = \frac{49}{2}^+$, $\tau = 12.6$ ns, 3n) and ^{149}Dy ($J^\pi = \frac{49}{2}^{(\pm)}$, $\tau = 28$ ns, 5n). This method selects states from a narrow region of angular

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momentum (i.e. $30\hbar$–$50\hbar$ for the 3n channel) as well as few regions of excitation energy roughly separated by the average energy per neutron emission. Fits to the isomer-triggered data indicate a very large nuclear deformation ($|\beta| \simeq 0.4$–0.5) and rather small resonance widths. So far, studies concerning the angular momentum dependence of the GDR strength distribution in the ^{154}Dy mass region have shown conflicting results [5,17–19], which we attribute primarily to the diminished selectivity.

The statistical γ-decay of the compound nucleus ^{154}Dy* has been studied using the reaction ^{114}Cd(^{40}Ar, xn)$^{154-x\mathrm{n}}$Dy. The beam of 173 MeV ^{40}Ar ions was produced with the AVF cyclotron at KVI in Groningen. Assuming complete fusion, the compound nucleus is formed with an average initial excitation energy of 69 MeV and an angular momentum distribution peaking at $50\hbar$ with a maximum value of $60\hbar$. High energy γ-rays were detected in a 10″ × 14″ NaI detector, placed perpendicular to the beam axis, at a distance of 60 cm from the target. Neutrons were discriminated from γ-rays by time of flight measured relative to prompt γ-rays observed with a multiplicity filter. A Compton suppressed Ge telescope was also placed close to the target [18]. The recoiling nuclei were stopped in a gold catcher foil 25 cm downstream of the target, corresponding to 33 ns flight time. There were eight 2″ × 3″ NaI detectors and one 5″ × 5″ NaI detector viewing the catcher foil to detect delayed γ-rays from the decay of high spin isomers; these were shielded from the target by 10 cm of lead. By requiring a delayed coincidence between the prompt high energy γ-rays and the γ-rays from the catcher foil, a selective trigger was obtained for events in which mainly the final nuclei ^{151}Dy and ^{149}Dy were populated. Furthermore, this coincidence requirement together with the requirement of a coincidence-fold for prompt γ's of ⩾2 set a lower limit of about $30\hbar$ on the compound nucleus spin. The selectivity of the isomer trigger was checked in the Ge spectrum. An extensive description of the experimental arrangement is given elsewhere [10].

In fig. 1 the isomer-triggered and the inclusive γ-spectra are compared, normalized in the energy range $E_\gamma = 2$–5 MeV. The γ-strength in the isomer-triggered spectrum is relatively enhanced by approximately a factor of three in the energy region $E_\gamma = 8$–14 MeV.

The inclusive γ-spectrum with no angular momen-

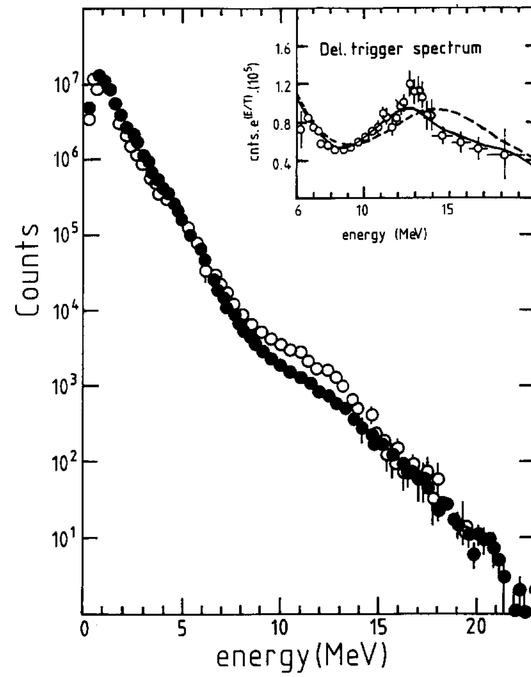

Fig. 1. Measured γ-ray spectra. Full dots: inclusive measurements, open dots: in coincidence with delayed isomer γ-ray emission. The insert shows the CASCADE fits to the isomer-triggered data. The solid line shows the calculation with the parameters of the best χ^2 in table 2, prolate nuclear shape; dashed line shows the spherical calculation. In the insert both the calculations and the data points have been multiplied by the same exponential function to enhance the features.

tum selection has been analyzed using the standard statistical model code CASCADE [20]. All calculated γ-ray spectra are subsequently folded with the detector response function. The best fit parameters found with a one-component lorentzian for the GDR strength distribution are given in table 1. This distribution is described by two free parameters: the GDR centroid energy (E) and the width (Γ). The total dipole strength was assumed to exhaust 100% of the TRK energy weighted sum rule (EWSR). Taking a two-component lorentzian distribution does not improve the fit [10]. The values of E and Γ found are typical for nuclei in this mass region, populated at similar excitation energies and spins [1,8,18].

The experimentally biased spectrum obtained via the isomer trigger cannot be described within the formalism as used in the statistical model code CASCADE, since the emission spectra can not be directly related to the final channels populated in the reac-

Table 1
GDR parameters obtained from a CASCADE code fit to the inclusive γ-spectrum.

E_{exc} (MeV)	$\langle J \rangle$ ($\hbar$)	a (MeV^{-1})	E (MeV)	Γ (MeV)	$c=\Gamma/E^2$
69	40	$A/8$	15.5 ± 0.5	10.6 ± 1.0	0.044 ± 0.004

Table 2
Best fit parameters obtained from a fit of decomposed CASCADE spectra to the isomer-triggered spectrum assuming 100% sum-rule strength. The estimated uncertainties are: ± 0.5 MeV for E_1, ± 0.7 MeV for E_2, and ± 0.005 for the width parameter c. The deformation parameter β can be determined to ± 0.05.

S_1 [a]	$\langle E \rangle$ (MeV)	E_1 (MeV)	E_2 (MeV)	Γ_1 (MeV)	c	β	χ^2/N
1.00	14.0	14.0	-	8.4	0.043	-	2.70
0.38	15.5	12.0	17.6	3.4	0.024	0.40	1.21
0.75	15.5	13.2	21.3	5.2	0.030	−0.50	1.49

[a] For γ-rays emitted at 90° with respect to the beam axis the relative strengths of each component of the strength distribution are $S_1=0.38$ and $S_2=0.62$ for a prolate nucleus rotating collectively and $S_1=0.75$ and $S_2=0.25$ for an oblate nucleus rotating non-collectively.

tion. A statistical model description of the channel-selected data can only be obtained if the decay of individual compound nuclei in an initial ensemble is followed by Monte Carlo techniques. A great disadvantage of the Monte Carlo technique is the long execution time necessary to obtain enough events of the infrequently ($\Gamma_\gamma/\Gamma_{tot} \simeq 10^{-3}$) occurring high energy γ-decay.

Here we propose a method to fit experimentally biased spectra, in this case isomer-triggered data, using the standard version of the CASCADE code [20]. The γ-decay spectrum calculated for γ-emissions from states above the particle decay threshold in a certain nucleus can be distributed in an approximate way among all residual nuclei that are still reachable. The amounts with which the γ-spectra are distributed are proportional to the normalized cross section for reaching these nuclei. The γ-emission below particle threshold is treated separately since it only contributes to the γ-spectrum associated with the nucleus from which it is emitted. The approach described here will be extensively discussed in a forthcoming article [10] on this subject. Extensive tests were performed to study the sensitivity of this method to the initial angular-momentum-dependent population cross section.

Using the above prescription, the spectra biased by the population of the isomers in ^{149}Dy, ^{151}Dy and ^{152}Dy can be calculated. In the calculations a lower spin cut-off of $30\hbar$ was introduced in agreement with the instrumental threshold as restricted by the event definition. The total spectrum biased by isomers populated in this experiment is then obtained by taking the sum

$$S_\gamma = S(^{149}\mathrm{Dy}) + aS(^{151}\mathrm{Dy}) + bS(^{152}\mathrm{Dy}) .$$

The factors a and b account for the differences in half-lives and in the multiplicity of the γ-rays depopulating the isomers. These factors are $a=0.62$ and $b=1.41$.

The experimental data have been fitted using a χ^2-minimization procedure. All calculations were performed with a level density parameter $a=A/8$ MeV^{-1} and a total resonance strength exhausting the EWSR and characterized by lorentzian functions for which the widths were constrained to $\Gamma_i = cE_i^2$. These constraints allow a more accurate determination of the GDR strength parameters. Both single- and double-lorentzian strength distributions were studied, representing spherical and axially deformed nuclei, respectively. Using the GDR strength distribution which describes the total spectrum (see table 1) results in a bad χ^2 for the isomer-triggered data. The best fit parameters found for the isomer-triggered data are listed in table 2. In the insert of fig. 1 the prolate (solid line) and spherical (dashed line) best fits are shown. To check on the correctness of the proposed procedure, Monte Carlo calculations [21] were performed using the best parameters resulting from the χ^2-fit. The Monte Carlo calculation essentially reproduces the results of our CASCADE calculations when comparable initial spin distributions are used. In fig. 2 the calculated best fit spectrum for the isomer-triggered data is shown decomposed in γ-ray spectra associated with specific residual nuclei. From these spectra it is evident that almost all GDR γ-rays ($E_\gamma \geqslant 9$ MeV) are emitted in the decay leading to ^{151}Dy, while the statistical part of the spectrum ($E_\gamma \leqslant 7$ MeV) originates mainly from γ-rays emitted by ^{149}Dy.

The two-component Lorentzian fits, both showing a good χ^2, indicate large nuclear deformations with a deformation parameter $|\beta| \simeq 0.4$–0.5. The deduced centroid energy $\langle E \rangle = 15.5 \pm 0.5$ MeV is, within errors, in agreement with the value expected from systematics for the GDR built on the ground state. The width parameter c is much smaller than the value obtained for the inclusive data, and is almost comparable to values obtained for GDR's built on nuclear ground states. A slightly better χ^2 is obtained by allowing the width parameters Γ_1 and Γ_2 to vary freely. This is particularly important to fit the sharper feature observed in the γ-spectrum at 13 MeV (see insert of fig. 1) which requires an even smaller value for Γ_1. However, the results do not differ significantly from the present results, i.e. a GDR centroid energy of 15.5 MeV, a large nuclear deformation ($|\beta| \simeq 0.4$–0.5) and a relatively small GDR width. The accuracy in the parameters shown in table 2 is mainly a result of the sharp structure at 13 MeV which determines the position and width of the first lorentzian, and partly due to the constraints on the sumrule and resonance widths used in the fitting procedure.

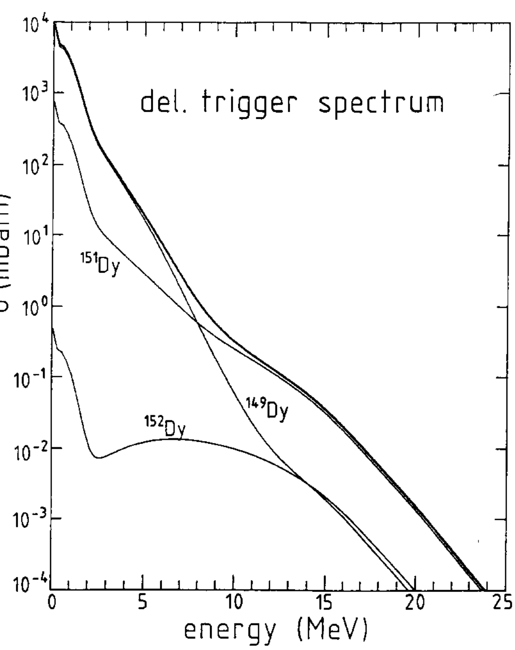

Fig. 2. CASCADE calculations with the best χ^2 fit parameters (see table 2) to the isomer-triggered data. The decomposition of the γ-rays emitted in decays leading to specific final nuclei (labels) is shown.

Previous to this analysis three other channel selective studies were published [14–16]. Stolk et al. [15] and Ataç et al. [16] also found that the GDR width extracted from the channel selected data is considerably smaller than the one from the inclusive data set, showing the importance of the sensitivity obtained by the channel selection.

The isomer-triggered spectrum represents photon decays from nuclear states selected from a rather small angular momentum region $30\hbar$–$50\hbar$ and localized in relatively small bins of excitation energy (caused by the constrained number of neutron emissions). The analysis of this data shows that the average nuclear shape for the selected states is highly deformed. The small widths found indicate that shape or orientation fluctuations are not large, and the average nuclear shape is maintained throughout the decay process. The small GDR width combined with values of $|\beta| \simeq 0.4$–0.5 indicate a stable and large average nuclear deformation in the angular momentum and excitation energy region associated with the decay leading to the final nucleus ^{151}Dy. This strongly suggests the existence of large deformations above the particle binding energy. That the nuclei in this mass region have a tendency to strongly deformed nuclear shapes is known from the observation of discrete superdeformed rotational bands [22–24]. The present data show, for the first time, the persistence of large stable deformations to medium temperatures (1.6 MeV) as deduced form the small resonance widths and large β values obtained from a fit to the GDR γ-spectrum.

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